AFRL-RY-WP-TP-2010-1241

HIGHLY STRAINED InGaAs/GaAs MULTIWATT VERTICAL-EXTERNAL-CAVITY SURFACE-EMITTING LASER EMITTING AROUND 1170nm (POSTPRINT)

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SEPTEMBER 2007

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AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
September 2007	Journal Article Postprint	01 November 2006 – 15 September 2007

4. TITLE AND SUBTITLE
HIGHLY STRAINED InGaAs/GaAs MULTIWATT VERTICAL-EXTERNAL-CAVITY SURFACE-EMITTING LASER EMITTING AROUND 1170nm (POSTPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62204F

6. AUTHOR(S)
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5d. PROJECT NUMBER
2002

5e. TASK NUMBER
IH

5f. WORK UNIT NUMBER
2002IH0E

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Sensors Directorate
Wright-Patterson Air Force Base, OH 45433-7320
Air Force Materiel Command
United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RY-WP-TP-2010-1241

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Sensors Directorate
Wright-Patterson Air Force Base, OH 45433-7320
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RYDP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RY-WP-TP-2010-1241

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Journal article published in *Applied Physics Letters*, Vol. 91, 2007. PAO Case Number: WPAFB-07-2178; Clearance Date: 21 Sep 2007. Paper contains color, and research was completed in 2007.

14. ABSTRACT
We develop and demonstrate a multiwatt highly strained InGaAs/GaAs vertical-external-cavity surface-emitting laser with a free lasing wavelength of around 1170 nm. This laser can be tuned from ~ 1147 to ~ 1197 nm. This low-cost compact wavelength agile laser can potentially provide high-power coherent light in a wide yellow-orange band by the intracavity frequency doubling.

15. SUBJECT TERMS
lasers, semiconductor

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	10	Robert Bedford **19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Highly strained InGaAs/GaAs multiwatt vertical-external-cavity surface-emitting laser emitting around 1170 nm

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(Received 7 August 2007; accepted 10 September 2007; published online 27 September 2007)

We develop and demonstrate a multiwatt highly strained InGaAs/GaAs vertical-external-cavity surface-emitting laser with a free lasing wavelength of around 1170 nm. This laser can be tuned from ~1147 to ~1197 nm. This low-cost compact wavelength agile laser can potentially provide high-power coherent light in a wide yellow-orange band by the intracavity frequency doubling. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2790838]

The semiconductor quantum wells in an optically pumped vertical-external-cavity surface-emitting laser (VECSEL) provide the broadband gain for the laser, resulting in a large wavelength tuning range.[1] Since the quantum well (QW) gain spectra can be accurately designed by using fully microscopic many-body model,[2] VECSELs provide wavelength agile laser sources through quantum confinement and a wide choice of constituent group II-VI and III-V material systems. This laser technology potentially provides an innovative approach to low-cost frequency agile lasers engineered for specific applications in near infrared and visible range (by intracavity frequency doubling).[3–8]

It is well-known that the 575–595 nm band is very attractive for adaptive optical telescope, quantum computing, dermatology, and ophthalmology applications.[9–11] Since it is hard to find laser materials with the direct transition in this band, nonlinear frequency conversions become major approaches to generate a yellow-orange laser. There are several methods of generating yellow lasers, including frequency doubling of Yb solid-state (fiber) lasers,[12,13] frequency doubling of Raman-shifted Yb (Nd) solid-state (fiber) lasers,[14,15] sum-frequency generation in solid-state lasers,[16] and frequency doubling of Bi-doped fiber lasers.[17] However, none of these methods can operate in the full 575–595 nm band with high output power.

Strained InGaAs/GaAs quantum well lasers cover a large wavelength range of 0.9–1.2 μm by altering the proportion of indium content. By means of intracavity frequency doubling of a VECSEL, the spectral range of 450–600 nm can be covered.[3–8] Considerable effort has been devoted to highly strained (high indium concentration) InGaAs/GaAs VECSEL for a longer wavelength; however, the longest tuned wavelength of InGaAs/GaAs VECSEL is still shorter than 1160 nm.[7] In this letter, we report on the development and demonstration of a highly strained InGaAs/GaAs VECSEL, which has a free lasing wavelength of over 1170 nm and can be tuned from 1147 nm 1197 nm. This laser has a multiwatt high-power performance even at the heatsink temperature of 45 °C. This low-cost compact wavelength agile laser can potentially provide a high-power coherent light in a wide yellow-orange band (575–595 nm) by the intracavity frequency doubling.

The design of the VECSEL structure is based on the rigorous microscopic quantum design approach and the three-dimensional optical/thermal modeling of the device. The former enables us to precisely determine the gain of the semiconductor quantum well and the gain peak shift as a function of temperature.[2] The latter enables us to close the design loop and optimize the VECSEL chip prior to wafer growth. Since the VECSEL will be the fundamental laser to generate yellow-orange light by intracavity second-harmonic generation (SHG), its free lasing wavelength is designed around 1170 nm. Using an intracavity birefringent filter allows us to tune the lasing wavelength and cover a broadband between 1150 and 1200 nm. The resonant periodic gain (RPG) structure of the VECSEL, grown on the GaAs substrate first, consists of ten 7 nm InGaAs QWs with GaAsP strain compensation barriers, separated by pump absorbing AlGaAs barriers. Distributed Bragg reflector (DBR) stack, consisting of 21 pairs of AlGaAs/AlAs, is grown on the RPG structure. In the simulation, the change of the refractive index of all layers with the temperature and the change of the refractive index of the QWs with carrier density in the wells are included. In addition, an inhomogeneous broadening of 15 meV for the InGaAs is also taken into account. To avoid thermal rollover, a detuning between quantum well gain peak

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0003-6951/2007/91(13)/131114/3/$23.00

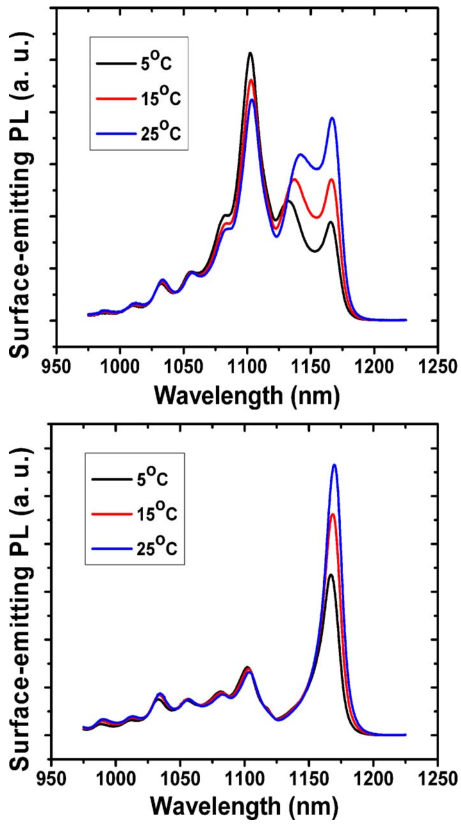

FIG. 1. (Color online) Surface-emitting photoluminescence of the VECSEL chip at the low pump density (top) and the threshold pump density (bottom).

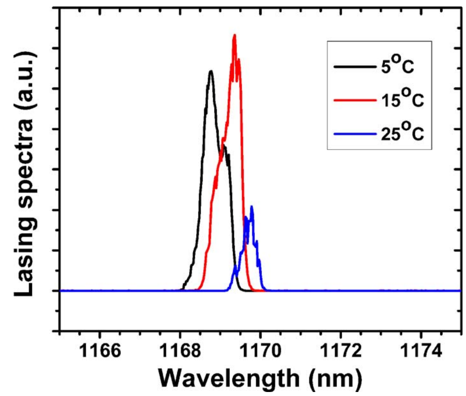

FIG. 2. (Color online) The free lasing spectra around the threshold.

and microcavity resonance of about 20 nm at 300 K is introduced in the design. The large detuning helps the VECSEL to have a robust performance at high temperature (over room temperature) in expense of an increased threshold power. The microcavity resonance (or subcavity resonance), determining the free lasing wavelength, relies on the knowledge of the refractive index of all layers in the structure. The errors due to the refractive index model and the growth may offset the designed lasing wavelength, but the broadband gain allows the VECSEL in conjunction with a birefringent filter to have a large lasing wavelength tuning range, giving us a freedom to control the laser wavelength.

Compared to the well-developed 980 nm InGaAs/GaAs optically pumped VECSEL, there are several challenges in the development of InGaAs/GaAs VECSEL operating around the wavelength range of 1150–1200 nm. One of the two major challenges is that it is difficult to grow the highly compressive strained InGaAs/GaAs quantum well in a complicated VECSEL structure. To overcome this challenge, we employ the low temperature metal-organic vapor-phase epitaxy to grow the VECSEL structure on GaAs substrate and balance the strain in the quantum well with GaAsP strain-compensating layer. The other challenge is the extraction of waste heat from the active region. Since there is no suitable barrier material which matches the crystal constant of GaAs substrate and can absorb pump emission from commercial 980 nm diode laser, we have to pump this long wavelength VECSEL by commercial 808 nm diode lasers. This lowers the quantum efficiency of the laser and generates more waste heat in the active region, passing through the DBR and dissipating into the submount of the chip. In addition, the lasing wavelength (around 1170 nm) is much longer than 980 nm such that the DBR mirror will be relatively thicker than that in 980 nm VECSEL, causing a higher thermal resistance in the device. To make a compromise between high reflection of the DBR mirror and minimum thermal resistance, we reduce the pair number of the DBR mirror to 21, providing 99.5% reflectance at the signal wavelength.

After the metallization, the epitaxal side of the wafer is mounted on a chemical-vapor deposited diamond by indium solder. The GaAs substrate is removed by wet chemical etching. The processed VECSEL chip is mounted on a heatsink for temperature control. To characterize the performance of the VECSEL, we measure the surface-emitting photoluminescence (PL) spectra at different temperatures and low pump density, the free lasing spectra and output power at different temperatures, beam quality at high-power operation, and tuning range in a high-Q cavity.

The surface-emitting PL spectrum is captured by a multimode fiber normal to the sample surface. The surface-emitting PL spectrum reflects the information of the quantum well PL and the resonance of the microcavity formed by the DBR and semiconductor/air interface etalon. It can be used as a tool to measure the characteristic of spontaneous emission inside the microcavity and to estimate the material gain peak and the lasing wavelength. In the measurement, we focus the fiber-coupled 808 nm pump emission on the chip with a spot size of 500 μm in diameter. The VECSEL chip is pumped at very low power (0.22 W) and at threshold pump power (9.6 W). At the very low pump power, we can eliminate the heating in the active region and obtain the pure information of the structure. At threshold pump power, the microcavity enhanced PL peak will approximately show the lasing wavelength. Figure 1 shows the surface-emitting PL at very low pump density (top) and high pump density around the threshold (bottom). According to the redshift rates of the quantum well gain peak and microcavity resonance with the increase of heatsink temperature,[18] the peaks around 1105 and 1166 nm in Fig. 1 (top) show two microcavity resonances and the peak between them (around 1140 nm) indicates the PL peak of the quantum wells. The major peak around 1170 nm in Fig. 1 (bottom) is the (microcavity) resonance enhanced spontaneous emission, indicating the free lasing wavelength around the threshold. Since the detuning between material gain peak and resonance peak is large, the laser threshold should be high; however, the performance at high temperature is robust and higher operation temperature results in lower laser threshold due to the fast redshift of the gain peak with the temperature.

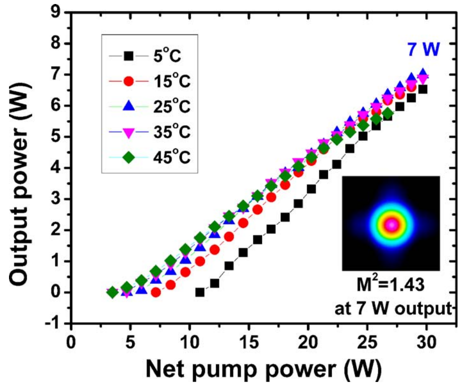

FIG. 3. (Color online) The performance of the VECSEL at the free lasing.

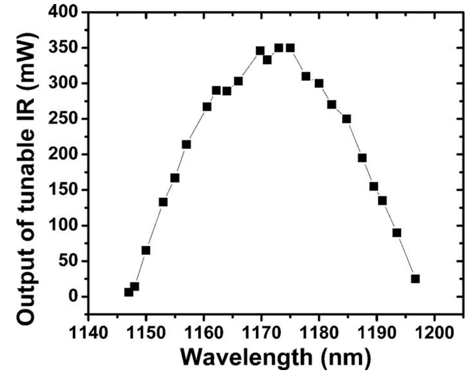

FIG. 4. The wavelength tuning of the VECSEL in a high-Q cavity with a birefringent filter.

We use a two-mirror (active mirror and output coupler) linear cavity to characterize the lasing performance of the VECSEL. The output coupler has a reflectance of 96% at signal wavelength and the radius of curvature of 300 mm. the pump spot size on the chip is still 500 μm in diameter. To obtain near TEM_{00} beam quality, the cavity length is adjusted to about 250 mm. Figure 2 shows the free lasing spectra around the laser threshold at 5, 15, and 25 °C (heatsink temperature). They are very close to the designed lasing wavelength (1170 nm). Increasing the pump power, of course, will redshift the free lasing wavelength. Figure 3 shows the output power as a function of pump power and heatsink temperature. The maximum power at room temperature (25 °C) can reach 7 W, with a small fluctuation of ±0.1 W. The VECSEL has a good performance even at 45 °C. Though the quantum efficiency is only 0.69 (808/1170), the VECSEL still has a good slope efficiency around 0.31–0.34. The laser threshold decreases as the heatsink temperature increases, which is in agreement with the prediction of the surface-emitting PL spectra. The inserted picture in Fig. 3 shows the high quality of VECSEL beam. The M^2 factor of the laser beam is only 1.43 at 7 W output.

Since this VECSEL is developed for the generation of yellow-orange light by intracavity SHG, we investigate its wavelength tuning behavior in the high-Q cavity. In the high-Q cavity, the output coupler has over 99.9% reflectance in the band between 1140 and 1300 nm. We insert a birefringent filter into the cavity near the Brewster angle. A small portion of circulating power inside the cavity is reflected by both surfaces of the birefringent filter. We acquire the tunable power from one side and the tunable lasing spectra from the other side. Figure 4 shows the tuning behavior of the VECSEL with a high-Q linear cavity when 16 W pump power is launched into the VECSEL chip at 25 °C. The laser has a large tuning range from 1147 to 1197 nm. The linewidth of the tuned spectra achieved by the birefringent filter is typically around 0.5–1 nm. Taking into account the loss introduced by the nonlinear crystal for the frequency doubling, we anticipate that this VECSEL can be a fundamental laser for generating coherent light in a broadband wavelength range between 575 and 595 nm.

In summary, we develop and demonstrate a multiwatt highly strained InGaAs/GaAs vertical-external-cavity surface-emitting laser, which has a free lasing wavelength of around 1170 nm and can be tuned from 1147 to 1197 nm. The laser shows a good performance at room temperature. This low-cost compact wavelength agile laser can potentially provide a high-power coherent light in a wide yellow-orange band by the intracavity frequency doubling.

The authors would like to acknowledge support from the U.S. Air Force Office of Scientific Research for a Phase II STTR Grant (No. FA9550-06-C-0044).

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